

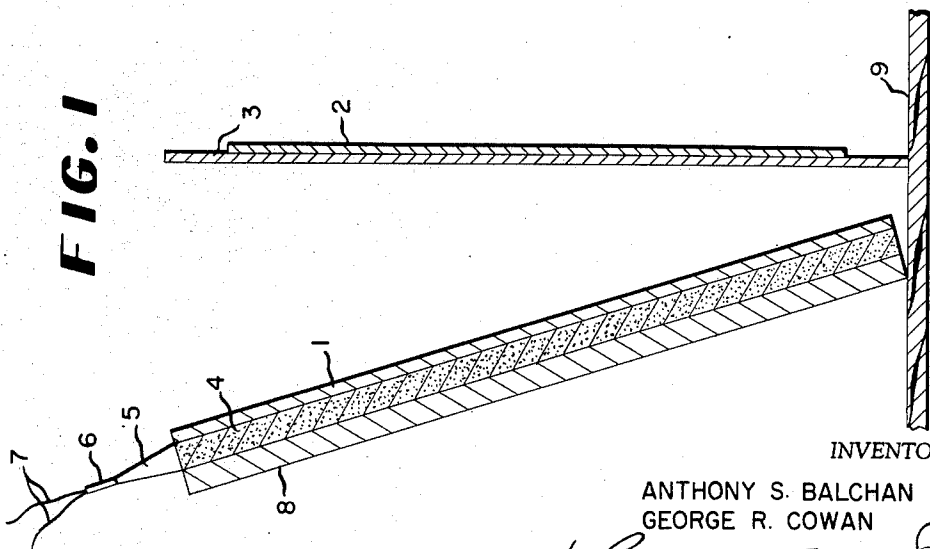
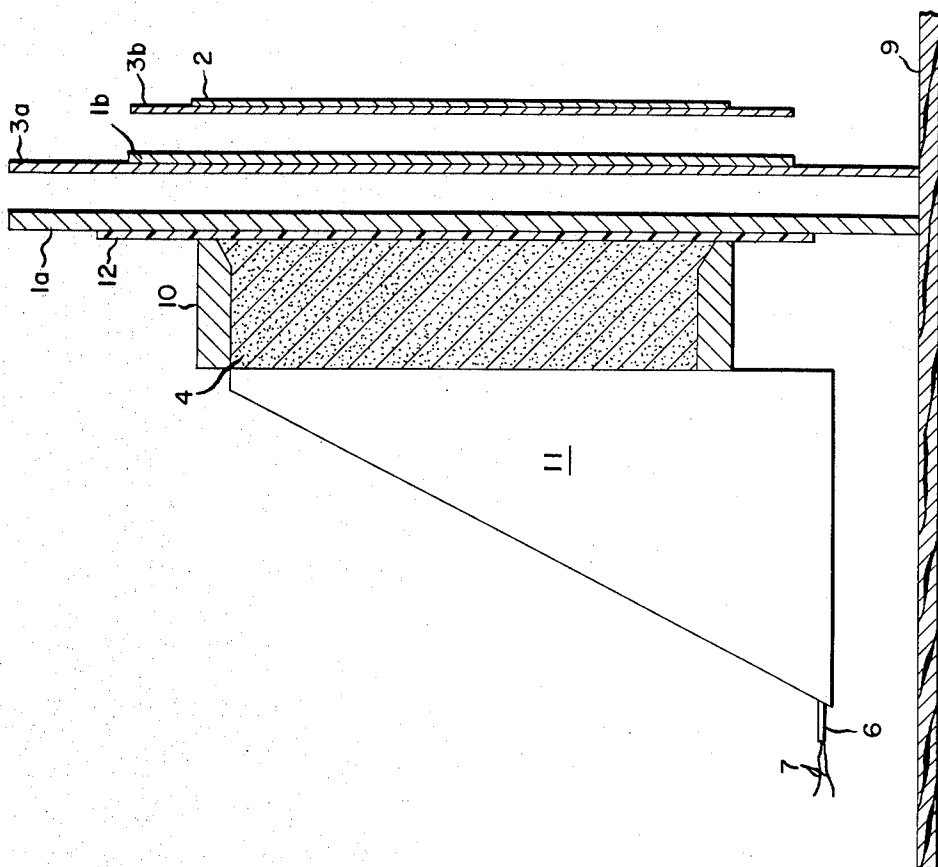
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APPARATUS FOR ACCELERATING PLATES TO HIGH VELOCITY

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APPARATUS FOR ACCELERATING PLATES TO HIGH VELOCITY

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The present invention relates to a method and apparatus for accelerating a plate to a high velocity, and more particularly to a method and apparatus for imparting a high velocity to a plate as a means of generating high-pressure shock waves.

Techniques for generating very high pressures, i.e., pressures above about 20 kilobars or 20,000 atmospheres, are important in that they enable the synthesis of materials which may be prepared only at such high pressures, and also in that they permit the study of the behavior of matter while it is subjected to such pressures. One technique that has been used to generate high pressures is the dynamic technique according to which an explosive is used to accelerate a projectile plate to high velocity. Collision of the high-velocity plate with a stationary target material results in shock pressures which are much higher than the original shock pressure generated by the explosive in the projectile plate. Since the shock pressure produced in the target material varies directly with the velocity of the projectile plate, the higher the pressure desired, the higher the projectile plate velocity must be. Heretofore, the achieving of high projectile plate velocities required that the plate be driven by means of explosives in contact with the plate. In such a system the plate velocity which it is possible to achieve is dependent upon the escape velocity of the products formed by detonation of the explosives, and cannot exceed this escape velocity. This means that velocities of about 8 millimeters per microsecond generally are the highest that theoretically can be achieved by the explosive-projectile plate method using conventional chemical explosives. Practical considerations on explosive charge size and precision requirements lower the maximum velocity achievable with this technique to about 5 millimeters per microsecond.

The present invention provides a process for accelerating a first plate to high velocity by impelling a horizontal surface of a second plate of greater thickness than the first plate against the free horizontal surface of a layer of passive buffer material having its other horizontal surface in continuous contact with a horizontal surface of said first plate and having a lower shock impedance than each of said plates, the collision surfaces of said second plate and buffer layer being in the same contour, i.e., they will mate with each other, and said first plate and buffer layer being freely moveable in the general direction faced by the first plate's free horizontal surface.

In the interest of brevity, the plate which is to be accelerated to a desired velocity by the present process will hereinafter be referred to as the "driven plate," and the plate which is impelled against, and thus collides with, the layer of buffer material will be referred to as the "driver plate."

The present invention also provides an apparatus for effecting the above process, which comprises a driven plate; a layer of passive buffer material in contact with a horizontal surface of said driven plate and forming a substantially continuous interface therewith, the buffer

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material having a lower shock impedance than said driven plate; a driver plate of higher shock impedance than the buffer material and greater thickness than said driven plate, a horizontal surface of said driver plate facing and being spaced from the free horizontal surface of said layer, said surfaces having the same contour; and means for impelling said driver plate against said layer of buffer material so that said free surface of said layer is impacted by said horizontal surface of said driver plate, said driven plate and layer being freely moveable in the general direction faced by said driven plate's free horizontal surface (i.e., the surface opposite said interface).

In an optional embodiment of the present invention, the procedure described above is adapted into a multiple-stage procedure, wherein the driven plate referred to above becomes a second driver plate and is caused to collide with a layer of buffer material in contact with a second plate to be accelerated; the latter plate then becoming the driven plate. This driven plate can in turn be used as a third driver plate, and so on for any desired number of collision stages. This means that in the one-stage embodiment, there is one driver plate and one driven plate. In the multiple-stage embodiment, there is the initial driver plate plus one or more additional driver plates, and one driven plate, i.e., the plate which is accelerated to the velocity which it is desired to achieve by the present invention. In the multiple-stage procedure, an increasingly higher velocity can be attained in each successive collision stage.

The term "plate" as used herein denotes a solid object having two essentially parallel surfaces of the same or about the same area, the distance between said surfaces being short relative to the dimensions of said parallel surfaces. "Parallel surfaces" denotes flat as well as curved surfaces. The term "layer" when used herein to refer to the buffer material denotes a mass which also has two surfaces of the geometric and dimensional character described for the term "plate," but which can be self-supporting or not self-supporting in nature. For example, one or both of the parallel surfaces of the layer can be a liquid surface. The parallel surfaces of the plate or layer described above, as opposed to the side or end surfaces thereof, are referred to herein as "horizontal surfaces"; however, this expression is not intended to limit the position of such surfaces with respect to the horizon in the present process and apparatus. Indeed, the plate or layer can have its horizontal surfaces substantially normal to the horizon. The horizontal surfaces preferably are flat but can be curved, in which event they preferably have a radius of curvature greater than about five times the thickness of the plate or layer. Side or end surfaces of the plate or layer can be flat or curved in any manner and to any desired degree. Typical of the forms which the plates and buffer layer can take are, for example, parallelepipeds (both flat and bowed), short solid cylinders or discs, and the like.

When reference is made herein to a horizontal surface of the driven plate in contact with the buffer layer, a horizontal surface of the driver plate colliding with the buffer layer, and a horizontal surface of the buffer layer contacting a plate surface, it is to be understood that such a contacting surface may constitute an entire horizontal surface of the plate of layer, or a portion or a horizontal surface thereof.

The term "buffer material" refers, by definition to a material which serves to bear the brunt of a collision. The

descriptive term "passive" as applied to the buffer material is used herein to denote that the buffer material per se exerts substantially no chemical or physical effect on the driven plate with which it is in contact. For example, the buffer material is unable to undergo, as a result of the impact of the driver plate therewith, a chemical reaction which releases energy sufficient to have a propulsive or disruptive effect on the driven plate with which the buffer layer is in contact. Also, the buffer material is passive to the degree that any chemical or physical change that it may undergo has no significant effect on the size and shape of the driven plate, and does not disturb the continuity of the interface between the driven plate and the buffer layer.

The term "collision surface" denotes herein the horizontal surface, or continuous portion of the horizontal surface, of the driver plate and the buffer layer which meet when the driver plate and buffer layer collide.

The term "shock impedance" as used herein refers to the resistance of a material to motion produced by an applied pressure. It is defined as a ratio of the change in applied pressure to the change in material velocity. When the material is compressed by a shock wave, the shock impedance is equal to the initial density of the material times the velocity of the shock wave passed through it, and thus varies with pressure. Both the driver plate(s) and driven plate used in the present invention have higher shock impedances than the buffer material.

In order to describe the invention more fully, reference is now made to the accompanying drawings, which illustrate suitable embodiments and wherein

FIGURE 1 is a sectional view of an assembly which can be employed in the one-stage embodiment of the present process; and

FIGURE 2 is a sectional view of an assembly which can be employed in the multi-stage embodiment of the process.

Turning now to the drawings in greater detail, in FIGURE 1 is a driver plate, 2 is the driven plate, i.e., the plate to be accelerated, and 3 is the buffer layer, 1, 2, and 3 in this case being made of metal and taking the form of parallelepipeds having flat horizontal surfaces. A uniform layer of explosive 4 is affixed to the surface of plate 1 opposite the surface facing buffer layer 3. A metal backing plate 8 is fixedly positioned on the opposite surface of explosive layer 4. The explosive-driver plate assembly is spaced from the buffer-driven plate assembly and positioned at an angle thereto. The initiation system of explosive layer 4 is comprised of (a) linewave generator 5 affixed to the edge of layer 4 farthest from buffer layer 3, and (b) electric blasting cap 6, having lead wires 7. The plate assemblies are supported on a base member, e.g., of wood, indicated by 9. Additional support members and means to hold the plates to the supports (e.g., adhesives or tape) are not shown since they are conventional. In this assembly, when blasting cap 6 is actuated, linewave generator 5 is initiated and detonates explosive layer 4 at a plurality of points on a line adjoining the surface of generator 5. Detonation of layer 4 hurls plate 1 against buffer layer 3, the collision being oblique or parallel depending on the detonation velocity of the explosive and on the angle formed by the driver plate 1 and the buffer-driven plate assembly. As a result of the collision, a shock wave is introduced into buffer layer 3 and through the buffer layer/driven plate interface into driven plate 2, causing acceleration of 3 and 2.

In FIGURE 2, 1a and 1b are driver plates, 3a and 3b are layers of buffer material, 2 is the driven plate, and 4 is a layer of explosive. A metal confining means 10 surrounds explosive 4, and plane-wave generator 11 is affixed to a flat surface of the explosive. Plane-wave generator 11 is initiated by blasting cap 6 having lead wires 7. A layer of a plastic film 12 lies between explosive layer 4 and plate 1a to assist in preventing plate break-up. The entire assembly rests on support 9. Upon

initiation of plane-wave generator 11 by actuation of blasting cap 6, explosive layer 4 is detonated along an entire flat surface thereof and a plane shock wave is thereby introduced into plate 1a, impelling the plate against buffer layer 3a, whose motion in turn causes driver plate 1b to impact buffer layer 3b and thereby to accelerate driven plate 2.

The present invention affords a means of imparting a high velocity to a plate without the limitations imposed by the conventional explosive-projectile plate method. In the conventional method, a projectile plate, in contact with an explosive, is accelerated to high velocity upon detonation of the explosive. The plate travels through a void and strikes a target plate on which a specimen to be studied is located. As has been stated before, this method is subject to the limitation that the maximum projectile plate velocity attainable is dependent on the escape velocity of the products formed by the detonation of the explosive. In the present invention, however, no such restriction exists owing to the fact that the projectile plate (i.e., the driven plate) is not in contact with an explosive and is not dependent on explosive power for its motion. On the contrary, in the present process the projectile plate is driven by the collision of a moving driver plate with a layer of a lower-impedance passive buffer material whose surface opposite the collision surface is in contact with the projectile plate to be accelerated. When the projectile (i.e., the driven) plate and the driver plate have essentially the same shock impedance, the layer of buffer material, at its surface opposite the collision surface, achieves a particle velocity higher than that of the driver plate, and a higher velocity is imparted also to the driven plate containing said surface of the buffer layer. When the driven plate has a shock impedance different from that of the driver plate, the velocity achieved by the driven plate is higher than that which it would achieve if it were impacted directly by the driver plate, i.e., if the buffer layer were absent.

When the shock impedance of the driver plate is equal to the shock impedance of the driven plate, the increase that can be achieved in the velocity of the driven plate over that of the driver plate in any particular case will depend (1) on the ratio of the shock impedance of the plates to the shock impedance of the buffer material, and (2) on the relative thicknesses of the plates and the buffer layer. Under the most favorable conditions, a driven-plate velocity about 2 times that of the driver plate can be obtained. Under otherwise equivalent conditions, higher driver-plate velocities result in higher driven-plate velocities. If the conditions employed in the process are such that the desired driven-plate velocity is not attained in the one-stage embodiment of this process, the multiple-stage embodiment can be employed to attain the desired velocity. Since each successive driver plate achieves a higher velocity than the previous one, the number of stages required to produce the desired over-all velocity increase, i.e., the desired driven-plate velocity, are employed.

The present invention requires that a layer of a passive buffer material having a lower shock impedance than the driver plate and the driven plate (1) have a horizontal surface in contact with a horizontal surface of the driven plate and (2) on its free horizontal surface opposite to that in contact with the driven plate, be struck by the driver plate. As mentioned above, the driven-plate velocity achieved depends on the relative shock impedances and thicknesses of the driver plate, driven plate, and buffer layer. The critical feature of the shock impedance relationship is that both the driver plate and driven plate have a higher shock impedance than the buffer material.

Regarding the impedance ratio of the driver plate to the driven plate, the presence of the lower-impedance buffer layer gives, regardless of the driver/driven plate impedance ratio, a driven-plate velocity which is higher than that achieved without this layer. However, best results are obtained when this plate impedance ratio essentially

equals 1, and this condition represents a preferred embodiment. Especially in the multiple-stage embodiment of the invention, it is preferable that the shock impedances of all of the driver plates and the driven plate be essentially the same in order to provide essentially the same velocity increase in each stage and therefore more predictable results.

The driver plate/buffer and driven plate/buffer impedance ratio will usually be at least about 1.5, since below this ratio there generally is no significant increase in the driven-plate velocity over the driver-plate velocity. Preferably, the plate/buffer impedance ratios are at least about 2. The optimum plate/buyer shock impedance ratio, i.e., the ratio which results in the maximum increase from driver-plate to driven-plate velocity, is dependent on the driver-plate/driven-plate thickness ratio employed. Assuming the buffer layer thickness to be essentially the same as the driven-plate thickness, as the driver-driven plate thickness ratio is increased from 2/1 to 4/1, the optimum plate/buffer impedance ratio for achieving maximum velocity increase rises from about 2.5 to about 8.5. Assuming the buffer layer thickness to be twice that of the driven plate, at a driver/driven plate thickness ratio of 4/1, the optimum plate/buffer impedance ratio for achieving maximum velocity increase is about 5. Maximum transfer of kinetic energy from the driver plate to the driven plate appears to increase as the plate thickness ratio decreases from 4/1 to 2/1 and the plate/buffer impedance ratio decreases from about 8.5 to about 2.5. Generally, on a practical basis, a plate/buffer impedance ratio higher than about 10 will not be employed.

The driver plate must be thicker than the driven plate. In the multiple-stage embodiment, wherein the driven plate from one stage becomes a driver plate for the next adjacent stage, the driver plates become less thick beginning with the first stage, and the driven plate, i.e., the plate in the last stage, is the thinnest of all. Although any number of stages can be employed, the number will usually be in the range of 1 to 10. In any stage, the driver plate should be at least about 1.5 times as thick as the driven plate, but preferably at least twice as thick, a driver/driven plate thickness ratio of 2 generally being the most useful ratio. Higher driver-plate to driven-plate thickness ratios, e.g., up to about 10, can be employed but ratios above about 5 generally do not appear to be practical since the small increase in velocity achieved with the higher ratios cannot be considered to be adequate compensation for the greater energy required to impel the thicker driver plate.

The particular shock impedance and thickness ratios employed will be selected on the basis of several factors, e.g., on whether or not an increase from driver-plate velocity to driven-plate velocity is to be achieved in one or several stages, the initial driver-plate velocity, etc. If only one stage is employed, it may be necessary to have impedance and thickness ratios which will give a large velocity increase from driver plate to driven plate to achieve the desired driven-plate velocity; on the other hand, ratios giving a smaller increase may be feasible in this procedure if the driver-plate velocity is suitably chosen. In the multiple-stage arrangement, the over-all velocity increase from the first driver plate to the driven plate in the final stage is controlled by selection of both the velocity increase per stage and the number of stages. Over-all efficiency of the process can be increased by employing a lower driver/driven plate thickness ratio, i.e., a ratio generally in the vicinity of 2, thereby reducing the velocity increase per stage, and simultaneously increasing the number of stages.

The passive buffer material can be any material or combination of materials (1) having a shock impedance such as to provide the requisite impedance ratio when used with driver and driven plates of selected higher

shock impedances, and (2) capable of exerting per se substantially no chemical or physical effect on the driven plate. With regard to its shock impedance, the buffer material should have a shock impedance of at least about 10^3 dyne-sec./cm.³ for the beneficial effects of the present process to be achieved. The density of the buffer material should be at least about 0.01 g./cm.³. This requirement limits the choice to liquids and solids. The only limit on the maximum shock impedance of the buffer material is that imposed by the availability of materials, the maximum being that which will give the required impedance ratios with available driver and driven plate materials having the highest shock impedances. With respect to the passiveness of the buffer material, as stated previously the material is one which, under the conditions used in the present process, i.e., when struck by the moving driver plate, is incapable per se of exerting a significant chemical or physical effect on the driven plate. While it might be assumed that use of a material having a propulsive effect, for example an explosive substance, would be necessary to achieve an increase in velocity from driver plate to driven plate owing to the added energy thereby supplied to the system, it has been found, on the contrary, that a passive material is far superior, and an energetic material undesirable, from the point of view of results and practical considerations.

Many materials fulfill the requirements for the passive buffer material. Any liquid having the properties prescribed above may be used, for example, water, organic liquids, and solutions and mixtures thereof. Colloids, suspensions, emulsions, or gels also may be employed. Typical solid materials capable of use are, for example, rubber and plastics, e.g., polyethylene, polystyrene, and nylon; and metals, especially the light metals, e.g., aluminum and magnesium and their alloys.

The buffer material may form the entire buffer layer, e.g., when the buffer material is in the form of a solid plate, or the layer may consist of the buffer material in a container therefor, e.g., a liquid or pulverulent solid in a container. Depending on the arrangement used to maintain the plates and buffer layer in their proper positions, the horizontal surfaces of the buffer layer may be surfaces of the solid or liquid buffer material itself, or container surfaces. If the buffer layer is joined to the driven plate by a thin film of adhesive material, preferably no thicker than about 0.0005 inch, the adhesive bond is considered a part of the buffer layer.

The horizontal surface of the buffer layer and the horizontal surface of the driven plate in contact therewith should form a substantially continuous interface in order to assure the achieving of a uniform particle velocity along the entire area of the free surface of the driven plate which it is desired to accelerate. The thickness of the buffer layer can vary from about 0.5 to 15 times the thickness of the driven plate for driver/driven plate thickness ratios up to about 10; in the preferred range of driver/driven plate thickness ratios, i.e., about 2-5, this buffer layer preferably will be about 1-5 times as thick as the driven plate. Although in principle there is no limitation on the maximum thickness of a given plate or layer, a practical limit on the thickness of the initial driver plate is about 6 inches, a one-inch thickness being adequate for many purposes.

The driver plates(s) and driven plate can be made of any material having a shock impedance such as to provide an impedance ratio of at least about 1.5 when used with a buffer material of a selected shock impedance. Accordingly, a material having a shock impedance as low as about 1.5×10^3 dyne/sec./cm.³ can be used. There is no limit on the maximum shock impedance of the driver and driven plates beyond that imposed by the impedance properties of available materials. Regardless of whether the driver plate and driven plate have the same or different shock impedances, these plates need not be made of the same material. Materials which can be employed

as plate materials are, for example, metals, plastics, ceramic materials, wood, fiberboard, etc. The single driver plate, or the driver plate in the first stage of a multiple-stage arrangement, should be made of a material which will not shatter under the effect of the means used to impel it, since the horizontal surface of the plate must contact the surface of the buffer layer. For this reason, this plate preferably is made of a non-brittle material, preferably a non-brittle metal. The driven plate preferably has a high shock impedance, since higher shock pressure can thereby be obtained, and therefore preferably is made of a metal. Thus, while many materials will meet the critical requirements of the plate components used in this invention, metals are preferred, particularly the relatively high-impedance metals such as tungsten, tantalum, vanadium, molybdenum, copper, lead, and nickel and their alloys, and the various steels, e.g., chromium-nickel stainless steel.

The relative positions of the horizontal surfaces of the driver plate and the layer of buffer material at the moment of collision are not critical. While essentially a continuous portion of the free surface of the layer of buffer material should be struck by a horizontal surface of the driver plate, all points of collision need not be reached at the same instant. This means that the driver plate can be driven against the layer of buffer material in a manner such as to cause parallel or oblique collision of the plate with the surface of the buffer material. Generally, a greater increase from driver-plate velocity to driven-plate velocity is achieved when parallel collision is employed, but practical considerations may in some situations rule in favor of the oblique collision method.

When the driver plate collides with the buffer layer at an angle so that the collision region is progressive (i.e., the area of the surfaces which have collided gets progressively larger, the collision region being a moving line of demarcation between surface portions which have collided and those which have not), and when the driver plate and buffer layer are subjected to a plastic shock wave, surface bonding may occur between the driver plate and the buffer layer. In order to avoid this, the velocity of the collision region, i.e., the rate at which the collision region progresses, along the colliding surfaces must in all stages be greater than 1.2 times the sonic velocity of any material in the system. The term "sonic velocity" as used herein refers to the velocity of the plastic shock wave which forms when an applied stress just exceeds the elastic limit for unidimensional compression of the particular material involved. The value of this sonic velocity may be obtained by means of the relation

$$C=\sqrt{K/\rho}$$

where C is the sonic velocity in cm./sec., K is the adiabatic bulk modulus in dynes/cm.², and ρ is the density in g./cm.³. Values of K for solids may be obtained from values of Young's modulus, E, and Poisson's ratio, ν , by means of the relation

$$K=E/(1-2\nu)$$

Values of ρ and K or E and ν are readily available in the literature (see, for example, American Institute of Physics Handbook, McGraw-Hill, New York, 1957).

Alternatively, the sonic velocity may be ascertained from published values of the velocity of the plastic shock wave as a function of the particle velocity imparted to the material by the shock wave in the manner described by R. G. McQueen and S. P. Marsh, Journal of Applied Physics 31, (7), 1253 (1960).

If literature data are unavailable, values of C may be obtained by carrying out shock wave measurements as described by R. G. McQueen and S. P. Marsh (loc. cit.) and in references cited by them. Alternatively C may be ascertained for solids from the relation

$$C=\sqrt{C_L^2-(4/3)C_S^2}$$

where C_L is the velocity of elastic compressional waves

and C_S is the velocity of elastic shear waves in the material. The required velocities of the elastic shear waves may be measured by well-known methods. For illustrative purposes, sonic velocity values for representative metals are given in the following table.

Metal:	Sonic velocity, m./sec.
Zinc -----	3000
Copper -----	4000
Magnesium -----	4500
Niobium -----	4500
Austenitic stainless steel -----	4500
Nickel -----	4700
Titanium -----	4800
Iron -----	4800
Molybdenum -----	5200
Aluminum -----	5500

In the present invention the driver plate is impelled against a free surface of the buffer layer, i.e., the driver plate is impelled a certain distance before striking the buffer layer. The distance travelled by the driver plate prior to collision should be at least that which allows the driver plate to attain a desired velocity. Specifically what this minimum distance is depends on such factors as the means used to impel the plate and the plate thickness. Generally a distance at least about equal to the plate thickness is required. While greater distances may be desirable in some cases, it is usually preferred not to exceed significantly the minimum distance required to attain the desired driver-plate velocity since undesired effects such as disrupting action on the plate may be introduced. While the distance required for the single driver plate in the single-stage embodiment, or the initial driver plate in the multiple-stage embodiment, to achieve the desired velocity before collision with the buffer layer may vary widely owing to the variety of means which can be employed to impel said plate, in any subsequent collision stages it will generally suffice if the driver in any stage travels a distance about equal to one-half its thickness before colliding with the buffer layer.

The velocity of the driver plate and consequently the means used to impel the driver plate are not critical features of the invention because the transfer of kinetic energy from the driver plate to the driven plate is independent of driver-plate velocity. However, since the invention finds its greatest utility in accelerating plates to very high velocities, the driver plate generally will have a velocity of at least about 100 meters per second.

Any of a number of means can be employed to impel the driver plate. For example, a condensed high explosive may be detonated in contact with the plate; or the driver plate may be accelerated in a gun by the burning of a propellant or by means of high-pressure inert gas. Other means which can be employed are detonating gaseous explosives, shock tube techniques, gravity, a magnetic field, etc. The selection of a means of setting the initial driver plate into motion will be made on the basis of various factors including ease of execution, whether one stage or multiple stages are used, and how high a velocity is required in the driver plate for the particular set of conditions employed.

A preferred means of setting the initial driver plate into motion consists in detonating a condensed, i.e., a solid or liquid, high explosive in contact with the plate. This technique has the advantage that it permits the attaining of higher velocities than other techniques and, at the same time, is relatively easy to carry out. A layer of detonating explosive is positioned adjacent the horizontal surface of the driver plate opposite the surface which is to contact the buffer material, the adjacent explosive-driver plate surfaces having the same contour and the quantity of explosive per unit area being uniform along the entire surface adjacent the plate. The explosive layer is initiated either along the free horizontal surface thereof or along a line from an edge depending on the positions of the driver plate relative to that of the buffer layer and

on whether the collision of the driver plate with the buffer material is to be a parallel or oblique one. Surface-wave and line-wave generators are well known to the art and any one of the devices can be used, for example, the surface-wave generators described in U.S. Patents 2,887,052, 2,999,458, and 3,016,831; and the line-wave generators described in U.S. Patents 2,943,571, 3,035,518, and 2,774,306. In the case of parallel collision, the explosive layer can be initiated by placing a surface-wave generator on the horizontal surface of the explosive layer opposite the horizontal surface thereof which is adjacent the driver plate, and aligning the plate essentially parallel to the layer of buffer material. Alternatively, parallel collision can be obtained by initiating the explosive layer along a line at an edge thereof while the explosive/driver plate assembly is arrayed at an angle to the buffer layer, the angle being so correlated with the velocity of detonation of the explosive layer that the portions of the plate adjacent the portions of the explosive layer which detonate earlier must travel farther to collide with the buffer layer surface than those adjacent the portions of the explosive layer which detonate later, all points on the driver plate surface opposite the surface contacting the explosive layer thereby impacting the buffer layer essentially at one time.

When the driver plate and the buffer material are to collide obliquely, the explosive layer also may be surface-wave initiated or initiated along a line at an edge thereof. For oblique collision, if the explosive is surface-wave initiated, the driver plate will initially be non-parallel to the layer of buffer material. If the explosive is line-wave initiated, the plate can be parallel or non-parallel to the layer of buffer material. In the case of oblique collision, the detonation velocity of the explosive, D , the angle, θ_1 , between the driver plate and the layer of buffer material prior to detonation, taken as a positive angle when the explosive is initiated at the edge farthest from the layer of buffer material, and the angle γ , through which the driver plate is driven into the buffer layer must be such as to give a flow velocity, V_A , of the driver plate into the collision region which is greater than 1.2 times the sonic velocity, C_A , of the driver plate and a flow velocity, V_B , of the buffer layer into the collision region which is greater than 1.2 times the sonic velocity, C_B , of the buffer material, C_A and C_B being determined as shown above, and V_A and V_B being given by the equations:

$$V_A = \frac{D \sin \gamma}{\sin (\gamma - \theta_1)} \frac{\cos (\gamma/2) - \theta_1}{\cos (\gamma/2)}$$

and

$$V_B = \frac{D \sin \gamma}{\sin (\gamma - \theta_1)}$$

wherein

γ is equal to θ_1 plus the angle between the driver plate and the buffer layer at the collision region, both of which can be measured by flash radiography. This measurement will tell whether a particular set of conditions of D and θ_1 will give the proper V_A and V_B .

When the driver plate is impelled by a means other than the detonation of a condensed explosive, the required collision region velocities will be obtained from a knowledge of the driver plate velocity, V_p , and θ_1 . In the case in which the driver plate is impelled so that it moves normal to its horizontal surface and collides with the buffer layer at an angle θ_1 , the collision region velocity along the surface of the driver plate is related to the plate velocity as follows:

$$V_A = V_p \tan \theta_1$$

and the collision region velocity along the surface of the buffer layer as follows:

$$V_B = V_p \sin \theta_1$$

The relationship between the collision region velocities and the driver plate velocity for the case in which the

driver plate is impelled through an angle γ can be determined from the equations given in the previous paragraph, substituting the term

$$\frac{V_p}{2 \sin \gamma/2}$$

for D therein.

When the driver plate and buffer layer are curved and arrayed non-parallel to one another, they are positioned in a manner such that conforming surfaces meet upon collision, i.e., a concave surface meets a convex surface of the same size. In this case, the angle between the driver plate and the layer of buffer material is the angle formed by a plane tangent to the driver plate at the center point of the collision surface of said plate and a plane passing through this point and parallel to a plane tangent to the corresponding layer surface at the center point thereof.

In the embodiment wherein an explosive means is used to set the driver plate in motion, any of the well-known high explosives, TNT, RDX, HMX, PETN, nitroglycerin, and mixtures containing them can be used so long as they may be provided as a uniform layer. Self-supporting explosive compositions such as those described in U.S. Patents 2,992,087, and 2,999,743 are especially well-suited for use in this process since they are readily formed into easily handled, tough, flexible sheets having a uniform quantity of explosive per unit area. Other compositions which can be used are the cohesive, gelatinous detonating explosives based on nitroglycerin, for example blasting gelatin, which can be formed into sheet-like uniformly dense explosive layers. Noncohesive solid and liquid high explosives can also be used by maintaining them in a suitable container. Castable explosives, for example those like amatol (TNT-ammonium nitrate mixture) or cyclotol (a TNT-RDX mixture), naturally can be readily cast into charges for use in the present process.

The mass of explosive used depends on the desired driver plate velocity, the mass of the plate, and the escape velocity of the detonation products, the mass required therefore differing with different explosives. The following table shows the velocity which can be achieved in 10-inch diameter circular steel plates of different thicknesses using 10-inch diameter layers of an explosive of different masses, the explosive being the sheet explosive described in U.S. Patent 2,999,743 and having a detonation velocity of about 7500 meters per second.

Explosive Mass (g./sq. in.)	Plate Thickness (in.)	Plate Velocity (km./sec.)
25	0.15	2.1
25	0.09	2.6
25	0.03	3.7
50	0.21	2.4
50	0.12	2.9
50	0.06	3.7
100	0.27	2.9
100	0.15	3.5
100	0.09	4.1

The means used to position the layer of buffer material and driven plate as required with respect to each other and with respect to the driver plate is not critical to the present invention, and any convenient means can be used so long as the driven plate and buffer layer are free to move in the direction in which they are to be impelled, i.e., generally in the direction faced by the driver plate's free horizontal surface, and the driver plate is free to run and collide with the buffer layer. Support means such as wooden blocks and frames can be used, for example, and the plates can be held in their respective positions by taping, an adhesive, or any other suitable means.

The area of the contacting driver plate and buffer layer surfaces must be at least as large as the horizontal surface area of that part of the driven plate which is to be accelerated. The alignment of the driver plate and the buffer/driven plate assembly and the direction of motion of the driver plate must be such that the driver plate contacts at least that area of the buffer layer surface directly opposite the surface forming an interface with that part of the driven plate to be accelerated.

The force which impels the driver plate can be applied to the entire plate or to a continuous portion thereof (as in FIGURE 2). If applied to the entire plate, the entire plate is impelled. If applied to a portion, the portion not so subjected will tend to break away, and the impelled portion will become the effective driver plate, which will then contact all or part of the free horizontal surface of the buffer layer depending on their relative sizes, a compressional wave being introduced into the buffer layer at the contacted surface. The surface of the driven plate at the buffer layer/driven plate interface can be the entire horizontal surface of the plate or a portion thereof. In the latter case, the portion of the driven plate subjected to the compressional wave transmitted across the interface becomes the accelerated driven plate. For practical reasons, when only a portion of the driver plate is impelled, only a portion of the buffer layer surface is contacted, or only a portion of the driven plate is accelerated, the effective or affected portion of the horizontal surface of the plate or layer preferably constitutes at least about 50% of the total surface area.

It is generally desirable to employ a driven plate which is smaller in horizontal-surface area than the driver plate in order to minimize the effect of lateral rarefaction waves.

The plates and buffer layer can all have the same edge contour or they may differ; e.g., one plate can be cylindrical, another a parallelepiped, etc., provided that the contact surface requirements are met.

When an explosive is used to impel the initial driver plate, an adhesive material can be used to affix the explosive layer to the driver. To provide confinement of the explosive and thereby to increase the impulse given to the driver plate from a given load of explosive, the explosive layer can be encased in a metal shell or backed by a metal plate. As shown in FIGURE 2, a layer of a plastic film, e.g., polyethylene, can be inserted between the explosive and the driver plate to prevent plate break-up during acceleration.

Any of the known techniques for measuring free-surface velocities can be employed to find the velocity of the driven plate. From among these techniques, one may employ, for example, a smear or streak camera or flash X-ray photography. Both methods allow computation of velocities directly from measured angles on the records obtained thereby.

The following examples serve to illustrate specific embodiments of the present invention. However, they will be understood to be illustrative only and not as limiting the invention in any manner.

Example 1

(a) A type 304 stainless steel plate 8 inches square and 0.025 inch thick and a 12-inch square, 0.0315-inch-thick magnesium plate are bonded together at horizontal surfaces thereof in a manner such that their geometric centers both lie on a straight line normal to the plates. A thin film of "Metalset" epoxy resin is applied to the magnesium plate, the steel plate is affixed to the film surface, and the plate assembly is pressed at a force of 5 tons to give an adhesive bond about 0.0005 inch thick. The steel/magnesium impedance ratio is ~ 3.5 .

(b) An explosive consisting of 50/50 pentolite (detonation velocity: about 7450 meters per second) is cast in the form of a 2-inch-high, five-inch diameter solid cylinder and encased in a 0.5-inch-thick open-ended steel

shell. The ends of the cylindrical charge are planed smooth, and one end surface is cemented under pressure to a horizontal surface of a Type 304 stainless steel plate 12 inches square and $\frac{1}{16}$ inch thick, said horizontal surface being covered with a $\frac{1}{32}$ -inch layer of polyethylene. A plane-wave generator of the type described in U.S. Patent 2,887,052 is affixed to the other end surface of the cylindrical explosive charge, and an electric blasting cap attached to the plane-wave generator.

(c) The assemblies formed as described in paragraphs (a) and (b) are positioned vertically so that the plates' horizontal surfaces are parallel and their geometric centers both lie on the same straight line normal to such surfaces, and the magnesium plate in the assembly formed according to paragraph (a) faces the steel plate in the assembly formed according to paragraph (b) and is spaced therefrom by 0.75 inch. The blasting cap is actuated, and the velocities attained by the steel plates determined by a streak camera technique. In this method the assemblies are silhouetted by a dim backlight of restricted aperture and the cutoff of light caused by the moving plates is recorded as an oblique trace on the film of the streak camera run at 3.2 mm./ μ sec. The velocities are obtained from the streak camera record from the slope of the lines representing the driver and driven plate motion. The measurement is made in a vacuum of 15 mm. to allow the plates to be visible behind the air shock. From the velocities measured in this manner, the velocity of the driven plate (0.025-inch-thick steel plate) is found to be 1.385 times the velocity of the driver plate ($\frac{1}{16}$ -inch-thick steel plate).

When the above procedure is repeated with the exception that the driven plate is 0.0315 inch thick, the driven plate velocity is 1.330 times the driver plate velocity.

Example 2

(a) A 1-inch x 5.5-inch Type 304 stainless steel plate and a 1.75-inch x 6-inch magnesium AZ31B-H24 alloy plate are bonded together in the manner described in Example 1.

(b) A layer of the sheet explosive described in U.S. Patent 2,999,743, and having a loading of 6 g./sq. in. and a detonation velocity of about 7500 m./sec., is affixed to a horizontal surface of a 2-inch x 8-inch Type 304 stainless steel plate $\frac{1}{16}$ inch thick. A $\frac{1}{4}$ -inch steel backer plate is affixed to the free surface of the sheet explosive to prevent spalling of the driver plate upon detonation of the explosive. A line-wave generator of the type described in U.S. Patent 2,943,571 is affixed to the sheet explosive along one of the shorter edges thereof, and an electric blasting cap is attached to the line-wave generator.

(c) The assemblies formed as described in paragraphs (a) and (b) are positioned vertically so that the plates' horizontal surfaces are oblique to each other, as shown in FIGURE 1, and their geometric centers both lie on the same straight line essentially normal to the horizontal surfaces of the assembly of step (a). The line-wave generator is at the edge of the explosive sheet farthest from the magnesium plate. The blasting cap is actuated, and the velocities attained by the steel plates determined by flash X-ray measurement of three angles, i.e., (1) θ_1 , the angle between the steel driver plate and the magnesium plate prior to detonation; (2) θ_M , the angle between the driver plate and the magnesium plate at the collision region; and (3) θ_2 , the angle of the driven plate with respect to its initial position. The collision region is allowed to travel 3 inches before the radiograph is taken. The plate velocities are calculated from these angles using the following equations:

$$V_1 = 2D \sin(\gamma/2)$$

$$V_2 = 2V_B \sin(\theta_1/2)$$

where V_2 is the driven-plate velocity, V_1 the driver-plate

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velocity, D the detonation velocity of the explosive, V_B the flow velocity of the magnesium layer into the collision region, and γ the angle through which the driver plate is driven into the magnesium buffer plate. Since

$$V_B = \frac{D \sin \gamma}{\sin (-\theta_i)}$$

and

$$\gamma = \theta_M + \theta_i$$
$$\frac{V_2}{V_1} = \frac{\sin (\theta_M + \theta_i) \sin (\theta_i/2)}{\sin [(\theta_M + \theta_i)/2] \sin \theta_m}$$

Thus it is seen that the ratio V_2/V_1 is determined only from the angles θ_i , θ_M , and θ_i and is independent of the detonation velocity.

The following table gives the V_2/V_1 ratio for a series of experiments carried out as described above using various buffer and driven plate thicknesses. In each case the driver/buffer and driven plate/buffer impedance ratio is ~ 3.7 , θ_i is 4° , and the distance between the driver and buffer at the closest points is 0.125 in. The detonation velocity of the explosive and the angle between the driver and buffer plates prior to detonation are such as to give an approximate collision point velocity of 10.87 mm./ μ sec.

Steel driven plate thick- (in.)	Mg plate thickness (in.)	V_2/V_1
0.006	0.050	1.671
0.012	0.050	1.519
0.025	0.050	1.302
0.0315	0.050	1.189
0.050	0.050	1.014
0.006	0.090	1.542
0.012	0.090	1.390
0.025	0.091	1.209
0.0315	0.091	1.114
0.012	0.0315	1.550
0.025	0.0315	1.372
0.0315	0.0315	1.215
0.050	0.0315	1.030
0.012	0.025	1.415
0.025	0.025	1.372
0.0315	0.025	1.250

Example 3

The procedure of Example 1 is repeated except that a two-stage collision is employed. Two buffer/driven plate assemblies (prepared according to paragraph (a) of Example 1) are used. In the first assembly, i.e., the assembly having the buffer plate impacted by the driver plate described in paragraph (b) of Example 1, the magnesium alloy and stainless steel plates are both 0.016 inch thick, and the stainless steel driven plate is 0.012 inch thick. The spacing between the second driver plate and the magnesium plate in the second assembly is 0.75 inch. In two identical experiments employing this arrangement, the average V_2/V_1 ratio (V_1 is the velocity of the first driver plate; V_2 is the driven plate velocity) is 1.76.

Example 4

The procedure of Example 2 is repeated except that two buffer/driven plate assemblies (prepared according to paragraph (a) of Example 2) are employed. In the first assembly, i.e., the assembly having the buffer plate impacted by the driver plate described in paragraph (b) of Example 2, the magnesium alloy and stainless steel plates are both 0.03 inch thick; in the second assembly, i.e., the assembly containing the driven plate, the magnesium alloy plate is 0.016 inch thick, and the stainless steel driven plate is 0.012 inch thick. θ_i is 4° , and the distance between driver plates and buffer layers at the closest points is 0.125 in. The approximate collision point velocity for each collision is 10.87 mm./ μ sec. In a series of three identical experiments using this arrangement, the average

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V_2/V_1 ratio (V_1 is the velocity of the first driver plate; V_2 is the driven plate velocity) is 1.73.

The foregoing detailed description has been given for clearness of understanding only and no unnecessary limitations are to be understood therefrom. The invention is not limited to the exact details shown and described, for various modifications which do not materially change the basic character of the invention or depart from the principle or spirit of the invention will appear to those skilled in the art.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. An apparatus for generating high-pressure shock waves which comprises a driven plate; a layer of passive buffer material in contact with a horizontal surface of said driven plate and forming a substantially continuous interface therewith, the buffer material having a lower shock impedance than said driven plate; a driver plate of higher shock impedance than the buffer material and greater thickness than said driven plate, a horizontal surface of said driver plate facing and being spaced from the free horizontal surface of said layer, said surfaces having the same contour; and means for impelling said driver plate against said layer of buffer material so that said free surface of said layer is impacted by said horizontal surface of said driver plate, said driven plate and layer being freely moveable in the general direction faced by said driven plate's free horizontal surface.

2. The apparatus of claim 1 wherein the driver and driven plates have about the same shock impedance, the ratio of driver and driven plate impedances to the impedance of the buffer material is at least 2, and the driver plate is at least twice as thick as the driven plate.

3. The apparatus of claim 2 wherein said driver plate, said driven plate and said buffer material are flat metal sheets and the impelling means is a condensed high explosive.

4. The apparatus of claim 2 wherein said plates and layer are flat and substantially parallel to each other, and said means for impelling the driver plate (includes (a) a uniform flat layer of condensed high explosive having one of its horizontal surfaces contiguous and substantially parallel to the surface of the driver plate opposite its said horizontal surface and (b) surface-wave generating means for initiating the free horizontal surface of said explosive layer.

5. The apparatus of claim 2 wherein there are a plurality of stages, each composed of one said driven plate and one said buffer layer, the driven plate for one stage being the driver plate for the next succeeding stage.

6. The apparatus of claim 2 wherein said plates and buffer layer are metallic, the driver to driven plate thickness ratio is about 2 to 5 and said layer is about 1 to 5 times as thick as the driver plate.

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